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Original Scientific Paper

PERFORMANCE ASSESSMENT OF SOLAR THERMAL HEAT STORAGE

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Abstract. *Over the past thirty years, there has been a notable increase in electricity usage within the residential sector of Europe. Final energy consumption in the EU residential sector has risen by 26.3%, with heating systems/electric boilers accounting for a substantial portion at 19.1% of final energy usage. Additionally, the combined utilization of solar energy for heating and cooling presents an opportunity to elevate solar thermal energy from primarily providing domestic hot water to becoming a major energy source for buildings, complete with hot water storage buffers. This study presents a model of a solar thermal system with heat storage, simulated using TRNSYS software, based on typical meteorological conditions in Nis, Serbia. The system is designed for heating domestic hot water, and scenario analysis is conducted to assess the advantages of solar thermal applications compared to electric hot water heaters. The findings suggest significant savings in electricity usage and costs are possible, although careful consideration is needed when sizing solar thermal systems to prevent stagnation during the summer months.*

Key words: *heat storage, solar thermal, household energy balance*

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1. INTRODUCTION

Over the last three decades, the electricity consumption of the residential sector in the European Union (EU-27) showed a great increment from 1990 to 2005 [1], and from 2005 to 2019 it is either in stagnation or its increase is minor; however, the residential sector is still the second biggest in electricity consumption, right after industry. Households use energy for various purposes: space and water heating, space cooling, cooking, lighting and electrical appliances, and other end-users (mainly covering uses of energy by households outside the dwellings themselves). Data on the energy consumption of households broken down by end-use, have been collected and published by Eurostat since 2017. In 2019, households, or the residential sector, represented 26.3 % of final energy consumption or 16.9 % of gross inland energy consumption in the EU [2]. During the 10-year period from 2009 to 2019, the consumption of electricity by households in the EU rose by 0.8 %. These figures on overall household electricity consumption are likely to be influenced, in part, by the average number of people living in each household and by the total number of households, both of which are linked to demographic events. Other influences include the extent of ownership and use of electrical household appliances and consumer goods as well as the use of energy-saving devices [2]. Furthermore, energy consumption for heating and cooling of a household is strongly affected by the level of energy efficiency measures implemented in the household (thermal insulation, quality of glazing, applied heating and cooling energy transformation technologies, etc.), whereas the electricity consumption is also affected by the energy efficiency rating of the household appliances.

The residential sector is the second most important final energy “consumer“ with almost 30% of the total electricity consumption. This is the main reason why the efficient use of energy by domestic appliances, along with the possibility of recovering and reusing their waste heat, is becoming more and more relevant.

1.1. Energy consumption in households in Europe and Serbia

The energy consumption of households in the EU decreased between 2005 and 2016 [8,9]. During the last 15 years, energy efficiency improvements in space heating and the use of more efficient electrical appliances, as well as behavioral changes driven by higher energy prices and the 2008 economic downturn all contributed to reductions in overall energy consumption in the household sector. Increases in the number of appliances, average size of dwellings, and number of dwellings partially offset these improvements [8].

Household energy consumption increased both in 2015 (by 4 %) and in 2016 (by 3 %) compared with 2014 and 2015 respectively. The relatively colder winters in these two years contributed to these increases. However, lifestyle changes such as more dwellings, more appliances per dwelling, and changes in heating behavior (e.g. higher indoor temperatures) also contributed. Energy efficiency improvements were not significant enough to counteract these effects. In fact, since 2013 a slowdown in the rate of the annual energy efficiency improvement has been observed year-on-year compared with the average annual rate of the 2005-2016 period. [8-11]

Energy use in the household sector differs widely between countries because of weather conditions, the state and age of the building stock and household appliances, the average size of the dwellings, the heating/cooling systems used, behavior (particularly with respect to cooking) and the level of implementation of energy efficiency measures. In 2016, per capita energy consumption in the household sector of the EU countries ranged from 0.2 tons of oil equivalent per capita (toe/capita) in Malta to 1 ton/capita in Finland [2, 8-11].

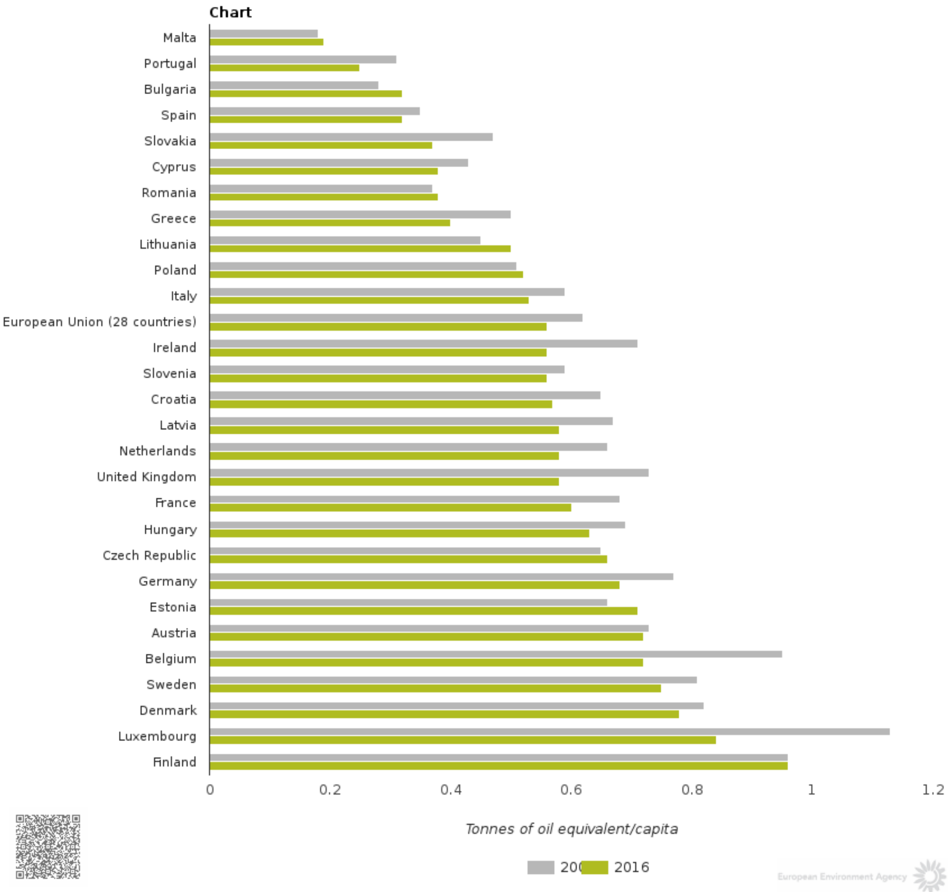

Fig. 1 Per capita final energy consumption of the household's sector, by country

As you can see in Figure 1. [8-11], the biggest consumer in Europe, from all 27 countries is Finland, and right next to Finland are Luxembourg, Denmark, Sweden. The explanation can be found in climate and temperature in the wintertime in those countries. For comparison, Finland used 67.46 TWh of electricity in 2020, while Serbia used 35.52 TWh. Like total energy consumption, the amount of electricity a country consumes in total is largely reflected by population size, as well as the average incomes of people in the given country.

There is a tendency for increased energy consumption in Serbia, while total dependency on imported energy, mostly petroleum and its products, is around 40% [4]. The housing industry's share in energy consumption amounts to 48% of total consumption, 65% of which refers to energy consumption in residential buildings ranging from 150 to 250 kWh/m2 on average [3]. [16]

1.2. Common appliances in households and their consumption

According to literature, the number of domestic appliances in the European Union is continuously growing and the same goes for how often that appliance is in use, as well as for the duration of their duty cycles. That is the reason why despite the continuous development of high-efficiency appliances, it is expected that electricity consumption in the residential sector continuously increases. Heating systems/electric boilers represent the highest share, about 19.1%, of the residential electricity consumption at the European level [1]. While the second, third and fourth place is reserved for refrigerators and freezers with energy consumption of almost 14.5%, then electric ovens, washing machines/dryers and dishwashers contribute to the electricity consumption of 6.6%, 7.2% and 3% respectively [12]. The European Union is required to meet standards that imply eco-responsiveness and information for the design of efficient household appliances. Based on the higher performances of the new appliances, in July 2011, new labelling directives were adopted introducing new energy efficiency classes (A+++, A++ and A+) to the already available (A-G). In addition, considering the most recent data available regarding [1,12-14] the performance and diffusion of household appliances, an assessment of the waste heat produced was carried out with the aim of evaluating the amount of thermal energy which should potentially be recovered and reused. At the European level, the most common household appliances are given in Table 1.

Table 1 Energy consumption analysis for appliances that are the biggest consumers

Appliance	Average energy consumption [kWh/cycle]	Temperature [ºC]
Refrigerators and freezers	640Wh/24h	35-50
Electric ovens	1.25	35-250
Dichwashers	0.8-0.95	40
Washing machines	1	30-35

According to the model given in the literature, parameters of active and stand-by consumption of an appliance are linked to the annual consumption model according to the following equation [3,6]:

$$E_{yearly} = \left(3600 \times 24 \frac{s}{day} \dot{E}_{stand-by} + f \sum_{n=1}^{n_{cycle}} \dot{E}_{cycle,n} \; t_{cycle} \right) \frac{365}{3,6 \times 10^{6}} \frac{daykWh}{W\,s} \tag{1}$$

where E_{yearly} is the mean consumption (kWh), $E_{stand\text{-}by}$ is the electric load of an appliance in stand-by, $E_{cycle,n}$ is the electric load during a mean consumption cycle (W), t_{cycle} is time step in the duration of a mean consumption cycle (s), and n_{cycle} is the number of time steps of the mean consumption cycle. The difference in behavior profile-electrical load on the typical working day and at the weekend was considered negligible. Basic energy-efficient rated appliances were included in the model: Television, electrical stove, Compact Disc player, personal computer, refrigerator with freezer, microwave oven, washing machine, and dishwasher. Thermal gain from the use of these appliances was included in the thermal balance of the building. The trend of change in daily electricity consumption due to climate changes throughout the year was synchronized with data from 41 by multiplying the time step value of electrical load by a monthly weight factor of the corresponding time interval [3,6,7].

1.3. Thermal storage and its function

Heat storage, also known as thermal energy storage (TES), generally involves the temporary storage of high- or low-temperature thermal energy for later use [15]. Heat storage

(HS) stores thermal energy for later use. TS systems are used in buildings and industrial heating/cooling applications, but in recent years it has become very common that even the residential sector increasingly uses heat storage. TES systems reduce peak demand, energy consumption, CO2 emissions, and costs. In literature, TES is described as “an advanced energy technology that is attracting increasing interest for thermal applications such as space and water heating, cooling, and air conditioning.”

Examples of heat storage applications include storage of solar energy for overnight heating, storing summer heat for winter use, winter ice for space cooling in summer, and storing electrically generated heat or cool power during off-peak hours for use during subsequent peak demand hours. In this regard, a heat storage system is in many instances a useful device for offsetting temporal mismatches between thermal energy availability and demand.

All heat storage systems have three functions:

1. Charge: a heat source is used to provide heat to the storage medium.
2. Storage: a medium is used to store the heat for later use. The storage medium may be located at the heat source, the discharge, or somewhere else.
3. Discharge: heat is extracted from the storage medium in a controlled fashion for use.

In addition, all heat storage systems have three basic components: a control system that makes it easier to charge and discharge the thermal storage, a heat exchanger to help transfer heat to and from the storage material, and storage material and, if applicable, a container for the storage material.

1.4. Optimal capacity of thermal storage

The combined use of solar energy for heating and cooling has the potential to upgrade solar thermal energy from a major DHW provider to a major building energy supplier. The simulation of the system is done in Trnsys software, and the scheme is given in Figure 2. A closed loop consisting of an evacuated tube solar collector and a variable speed pump provides the hot stream of a heat exchanger within a sealed tank filled with an energy storage medium such as non-potable water. Water is drawn from the mains through another heat exchanger within the same tank and preheated before delivery to the storage tank, where it is further heated by gas (if necessary) before use.

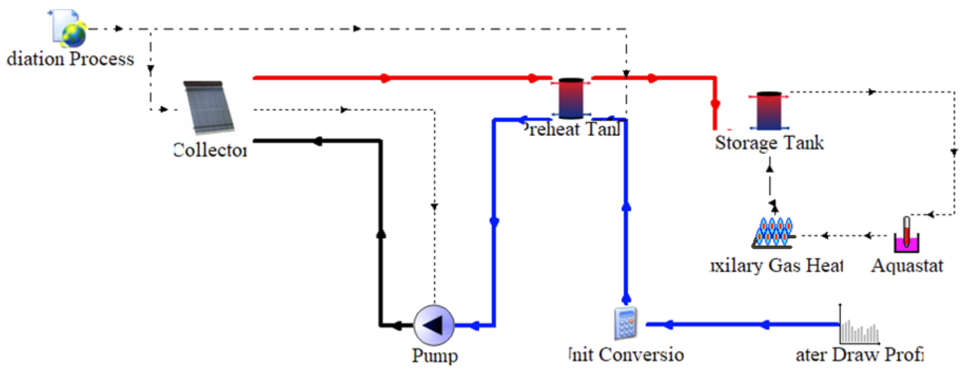

Fig. 2 Schematic representation of the considered system

As it is given in Figure 2, we have two solar collectors, one Preheat storage tank and one Storage tank. The solar collectors are chosen to respond to demands so that the system does not enter the realm of stagnation, and it is the reason why we have a reheater (also presented in Figure 2).

The components that we used in our simulation are:

1. Radiation Processor- provides solar radiation data, ambient temperature, and water mains temperature;
2. Collector -models evacuated tube solar collector; variable behavior;
3. Pump- Variable speed pump, controlled by collector behavior;
4. Preheat Tank- sealed tank with dual heat exchangers to provide preheating of mains water 0.5 m3;
5. Water Draw Profile - instant water draw profile used by SRCC;
6. Unit Conversion - converts from GPM to kg/hr;
7. Storage Tank- stores preheated water 1 m3;
8. Auxiliary heater - heats water in storage tank if necessary;
9. Aquastat -generates a control signal for the gas heater based on storage tank temperature.

2. Results and Discussion

The results obtained by simulation are presented in the next few figures. The first simulation is given for the whole year, 8760h. The heat exchanger fluid is water with a density of 1000[kg/m3], thermal conductivity of 2.14 [kJ/hmK], and specific heat of 4.19 [kJ/kg K]. Tank properties are: number of tank nodes is 8, the tank volume is 1[m3], top and bottom loss coefficient is 5[kJ/hm2K], and initial tank node temperature is 55[ºC]. Solar collector has an array area of 2[m2], the number of nodes is 10, and the flow rate per unit area is 50[kg/hm2]. Aquastat is set so that fluid inlet temp. is 20[ºC], and setpoint temperature for stage is 50[ºC]. Hysteresis +/- 2 [ºC]. Preheater has a heating capacity of 16200[kJ/h]. The results in the paper are presented for a typical meteorological year, for the solar radiation data for Nis, Serbia, with 1h timestep resolution.

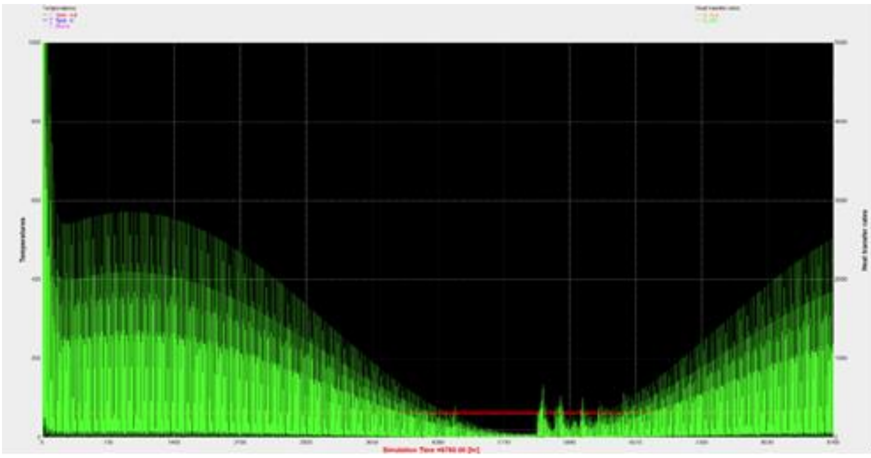

Fig. 3 Annual solar thermal system results (green – heat exchanger transferred energy in kJ/h, red – tank outlet temperature in ºC, blue Tank inlet temperature in ºC, purple – mains water temperature in ºC) ¶

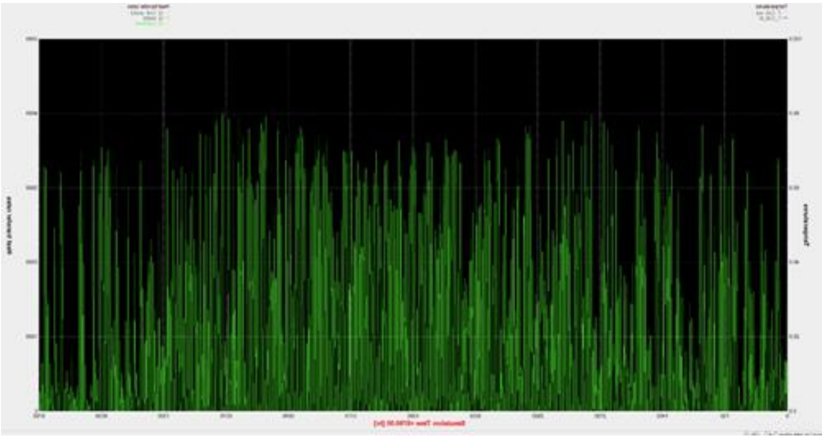

Fig. 4 The amount of the amount of solar radiation in kJ/h

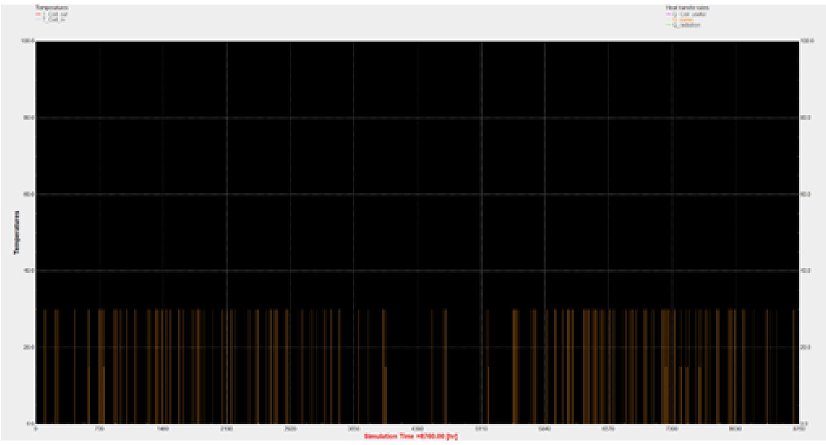

Fig. 5 Electricity used by the pump of the solar system in kJ/h

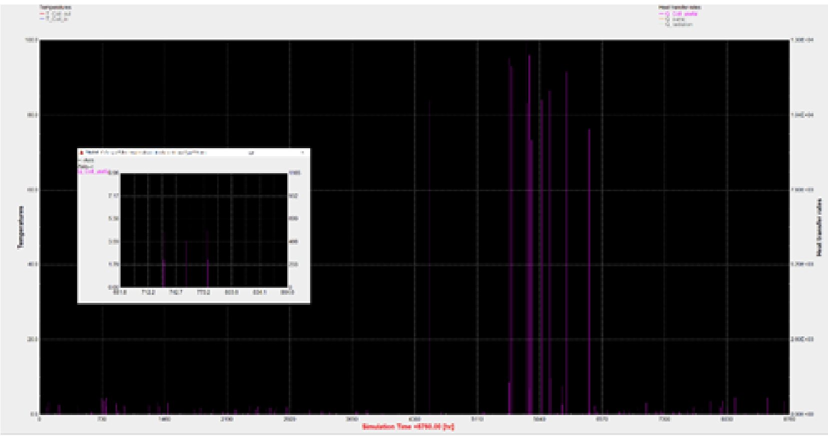

Fig. 6 Useful heat exchange from solar collector

In the first part of the year (first six months) and in the last three months of the year, the amount of useful heat given through solar collectors is much smaller than in July, August, and September. The explanation is simple – those are the winter, fall and early spring months. Furthermore, the utilization of the solar system is also dependent on the control system and the use of heat by the heat exchanger. Hence since the initial temperature of the tank is relatively high (55ºC), the water is heated using the heater, since the solar radiation is insufficient. In the summer period, the solar radiation is sufficient for the assumed consumption load, however, in the rest of the year it is utilized only when the temperature conditions are such, that the temperature is low enough to utilize solar energy, and the temperature in the solar collector in the same timestep is high enough for heating the tank(s). If this condition is not met, the tanks are heated by the heat exchanger-heater, resulting in poor effectiveness of the solar system, except in the hot summer munts. In the figure, you can see zoomed results for the January period.

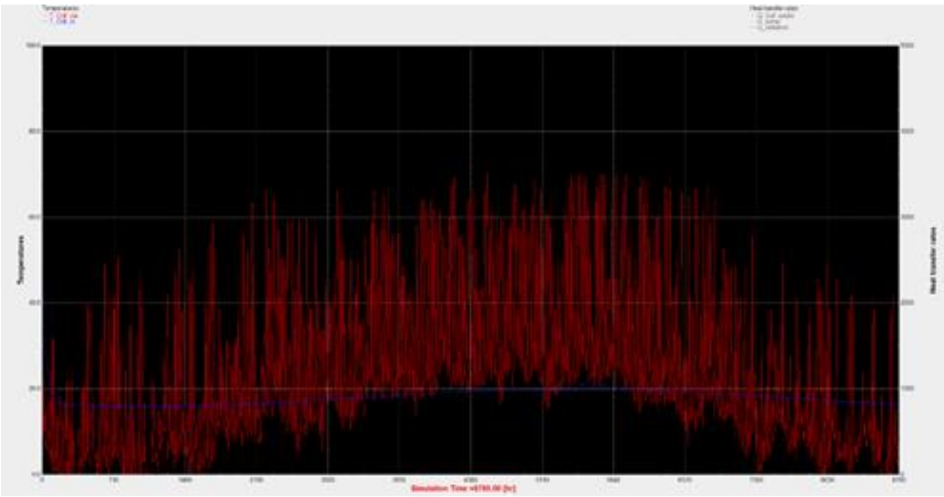

Fig. 7. Temperature inlet and outlet for Solar collector

As shown in Figure 7, the inlet temperature is practically the same throughout the year, no matter what time of day or year is, and as can be seen in Figure 7 that is not the case for outlet temperature. The inlet temperature is around 20 [ºC], with small fluctuation in the first three months of the year, and outlet temperature varies through the day, while at night it is lower, which depends on the time of the year. The highest outlet temperature is from May till September, and it can go to 73[ºC].

3. CONCLUSION

This paper presents and analyses the current state of energy consumption in households in the European Union. It is concluded that sanitary hot water accounts for almost 20% of household electricity consumption. An annual simulation of the solar evacuated tube collector system with an auxiliary heater is made for a typical meteorological year in Serbia. The simulation indicated that the design of the system and choice of hot water tank desired temperature level, as well as dynamics of the consumption and availability of solar energy can strongly affect the effectiveness of the solar system. As the simulation results show, if the hot water tank temperature is set too high, solar collectors may provide insufficient heat flux for most of the year, except for the summer period. The solar systems are sized this way, i.e. based on the minimum heat demand in the hottest summer periods, to avoid the so-called solar thermal system stagnation, which can lead to system damage. Therefore, for the high desired tank temperatures, the auxiliary heater is responsible for meeting most of the hot water energy demands. Different scenarios can be expected in the case of lower desired tank temperatures, but this can be analyzed in some future research and is omitted from this study.

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PROCENA RADNIH KARAKTERISTIKA SOLARNOG AKUMULATORA TOPLOTE

Tokom proteklih trideset godina, došlo je do značajnog povećanja potrošnje električne energije u stambenom sektoru Evrope. Finalna potrošnja energije u stambenom sektoru EU porasla je za 26,3%, pri čemu sistemi grejanja/električni kotlovi čine značajan deo od 19,1% finalne potrošnje energije. Kombinovano korišćenje solarne energije za grejanje i hlađenje predstavlja priliku da se solarna toplotna energija podigne sa primarnog snabdevanja tople vode za domaćinstvo do toga da postane glavni izvor energije za zgrade, zajedno sa baferima za skladištenje tople vode. Ova studija predstavlja model solarnog termalnog sistema sa akumulacijom toplote, simuliran korišćenjem softvera TRNSIS, zasnovan na tipičnim meteorološkim uslovima u Nišu, Srbija. Sistem je dizajniran za zagrevanje sanitarne tople vode, a analiza scenarija je sprovedena kako bi se procenile prednosti solarne primene u poređenju sa električnim grejačima tople vode. Rezultati ukazuju na to da su moguće značajne uštede u korišćenju električne energije i troškovima, iako je potrebno pažljivo razmatranje kada se dimennzioniše ovakav sistem kako bi se sprečila stagnacija tokom letnjih meseci.

Ključne reči: *akumulatori toplote, solarni sistemi, toplotni bilans za objekte u rezidencijalnom sektoru*